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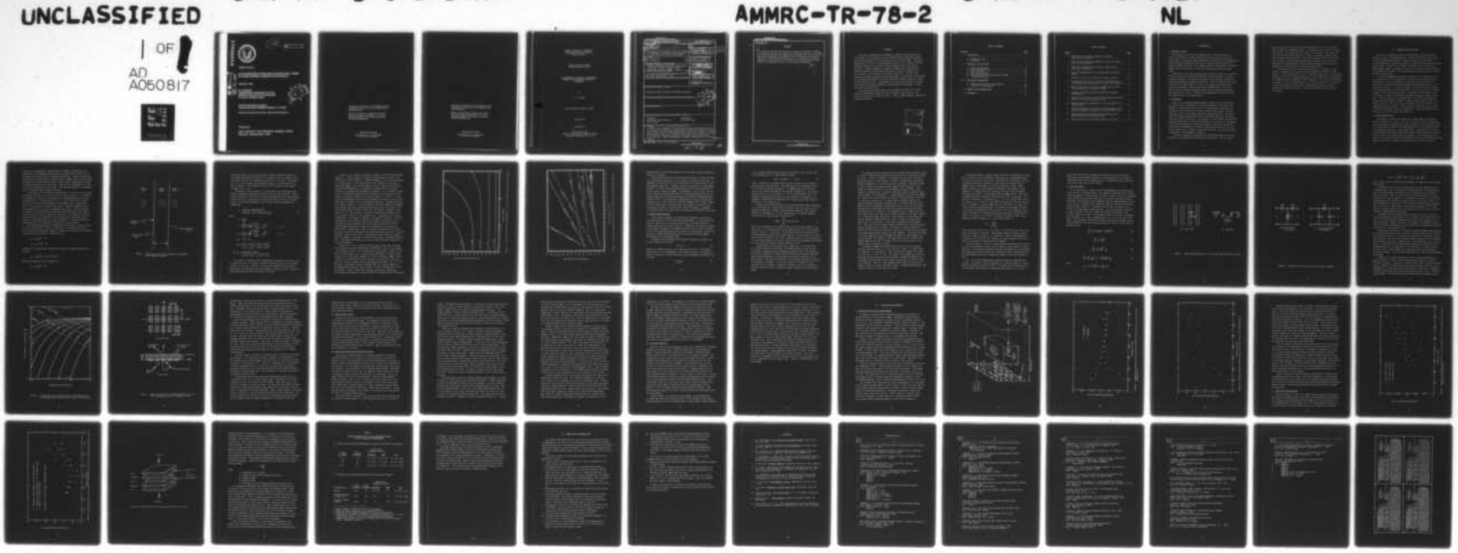

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AMMRC TR 78-2

ELECTROMAGNETIC SHIELDING OF STRUCTURAL FOAMS BY USING INTERNAL CONDUCTIVE MATERIALS

JANUARY 1978

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INTERIM TECHNICAL REPORT
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Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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Interim Technical Report
EES/GIT Project A-1961

ELECTROMAGNETIC SHIELDING OF STRUCTURAL FOAMS BY USING INTERNAL CONDUCTIVE MATERIALS

by

D. G. Bodnar

Contract Number DAAG46-77-C-0027

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This report summarizes the preliminary analysis performed during the first phase of the program to assess the RF shielding effectiveness obtainable by using internal conductive materials in structural foams. The major emphasis was on the use of carbon/graphite fibers as the conductive material although consideration was given to metalized glass fibers and to metal particles. Several mathematical analysis techniques were considered (cont'd) over

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ABSTRACT

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ABSTRACT

This report summarizes the preliminary analysis performed during the first phase of the program to assess the RF shielding effectiveness obtainable by using internal conductive materials in structural foams. The major emphasis was on the use of carbon/graphite fibers as the conductive material although consideration was given to metalized glass fibers and to metal particles. Several mathematical analysis techniques were considered for assessing shielding effectiveness including the method of moments, wire grid analysis, meteorological, and plane wave analysis. The plane wave analysis technique was deemed the most applicable. Calculations are presented of shielding effectiveness in the HF through UHF frequency range for various material characteristics. Recommendations are also presented on test panels that should be fabricated during the second phase of the program to verify the theoretical predictions.

This work was performed under contract DAAG46-77-C-0027 for the Army Materials and Mechanics Research Center, Watertown, Massachusetts. The contract monitor for the Army was Alan M. Litman, Organic Materials Laboratory, Composites Division.

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I. INTRODUCTION

A. Purpose of Study

The principal objective of the program was to assess the ability to achieve RF shielding by adding conductive materials internally to structural foams. The primary conductive material of interest was carbon/graphite fibers although consideration was given to metalized glass fibers and to conductive metal particles. The ultimate goal of the analysis is to provide design input for fabrication of radio set housings made from structural foams.

This report covers work performed under the first phase of the contract. During this phase a review was performed of the applicability of several analysis techniques to shielding calculations for structural foam that is internally loaded with conductive materials. Data were compiled that permit a selection of sample panels to be built for testing during the second phase of the program. Current panels made by AMMRC have a conductivity that is about an order of magnitude smaller than is required for adequate shielding (50 dB or more). Materials are recommended that should increase the conductivity to the required level.

B. Background

There is an increasing tendency among producers of both military and civilian electronic equipment to use plastic housings for the electronic equipment. The trend to replace cast or fabricated metal housings with plastics has been driven by the desire to obtain light weight, corrosion resistance, parts consolidation, and other economic benefits. Typically, injection molding, compression molding, reinforced plastics or structural foams are used for fabrication. The tendency to replace metal housings with plastic housings has a very pronounced effect on the ability of the housing to shield electromagnetic energy from leaving or entering the structure. The ability of the material to block or attenuate RF varies with its electrical conductivity. Plastics, being good insulators, are therefore highly transparent to electromagnetic radiation.

The basic technique for improving the RF shielding ability of plastic housings is to reintroduce the shield into the plastic. This is done by

making the plastic surface electrically conductive so that it will reflect and/or absorb electromagnetic energy. To accomplish this, a layer of conductive material can be applied to the surface of the casing. The conductive layer may take the form of metal foil, tape or screening, plating, vacuum metallizations, metal spraying or conductive coatings. Each of these operations involves a separate manufacturing process and some are not readily applicable to complex shapes. Many of these techniques have been tried in industry and found effective for different applications.

A technique which has not been used and which is the subject of this study is to impregnate the plastic with carbon/graphite fibers or metallic powders. These carbon/graphite fibers or metallic powders will be distributed throughout the plastic housing and, because of their good electrical conductivity, should provide a high degree of RF shielding. Since they are distributed throughout a volume of casing instead of just at the surface, it is expected that the shielding properties of the carbon/graphite fibers or metallic powders may be better than that of a thin sheet applied to the surface of the housing.

II. THEORETICAL CALCULATIONS

This section summarizes some of the theoretical analyses performed during the study. The emphasis herein is directed toward obtaining trends in shielding performance based on changes in material characteristics. Several mathematical analysis techniques are reviewed for assessing shielding effectiveness. Included are the method of moments, wire grid analysis, meteorological models, and plane wave analysis. Calculations are presented of shielding effectiveness in the HF through UHF frequency range for various material characteristics.

A review of mathematical analysis techniques was an essential part of the program because of the complicated nature of the shielding structure. Specifically, it is anticipated that the conducting particles will be essentially randomly distributed throughout the structural foam due to the manufacturing process. The density (number of particles per unit volume) of conducting particles can be varied over a wide range of values by simple changes in the manufacturing process. In addition, the frequency range of interest is large, covering HF through UHF frequencies (roughly 1-1000 MHz). Finally, the material parameters may vary greatly from moderately conducting carbon/graphite fibers, to highly conducting metal powders, to magnetic powders. This wide range of parameters creates a difficult electromagnetic analysis problem. The next several subsections discuss some of the analysis techniques that were considered. A plane wave analysis technique was selected as the most applicable one.

A. Plane Wave Analysis

The analysis of Section IIC shows that a large number of contacting fibers is required in a panel to provide a reasonable amount of shielding. Since the fibers themselves and the fiber contacts are lossy and since there is a large number of fibers, one might expect that a lossy conductor model would adequately describe a fiber loaded panel. Consequently, an analysis was performed of the panels representing them as lossy conductors and using a plane wave as the field incident on the panel. For HF frequencies and above, it is usually necessary to consider only plane wave fields and not near magnetic and electric fields in addition because the shield is usually

electrical far enough away from the source of energy. Plane waves arise naturally in electromagnetic (EM) analysis since plane wave functions form a complete set of functions for representing RF fields. Thus, any arbitrary EM field can be represented by a sum of properly weighted plane wave functions. In addition, RF fields behave locally as plane waves at large distances from a spacially finite source of RF energy. Thus, RF fields impinging on shields can often be represented by plane waves. Only normal incidence is considered since it indicates major trends in the data.

An evaluation of the shielding effectiveness of a panel can be performed by modeling the panel as an infinite plane as shown in Figure 1. To simplify the mathematics, the panel is represented as a homogeneous material having a permeability μ_0, a permittivity of $\varepsilon = \varepsilon_r\varepsilon_o$, and a conductivity σ where μ_0 and ε_0 are the free space permeability and permittivity, respectively, and ε_r is the dielectric constant of the panel. Next the incident RF field is approximated by a plane wave impinging on the panel at normal incidence. A portion of the incident wave is reflected by the panel due to the change in electrical properties it exhibits to the wave. The remainder of the wave enters the panel, is attenuated by the lossy material in the panel, and a portion of this energy exits the panel into Region 3. Multiple reflections inside the panel must be properly accounted for in the analysis.

The equations describing the transmission of plane waves through a plane sheet of lossy material at normal incidence may be formulated as follows. The electric field intensity in Region 1 consists of an incident and a reflected field which may be written, respectively, as

$$E_i = E_0 e^{jk_1 z - j\omega t}$$

$$E_r = E_1 e^{-jk_1 z - j\omega t}$$

In Region 2, the field must be expressed in terms of positive and negative waves as

$$E_s = (E_2^+ e^{jk_2 z} + E_2^- e^{-jk_2 z}) e^{-j\omega t}$$

while the transmitted field in Region 3 is

$$E_t = E_3 e^{jk_3 z - j\omega t}.$$

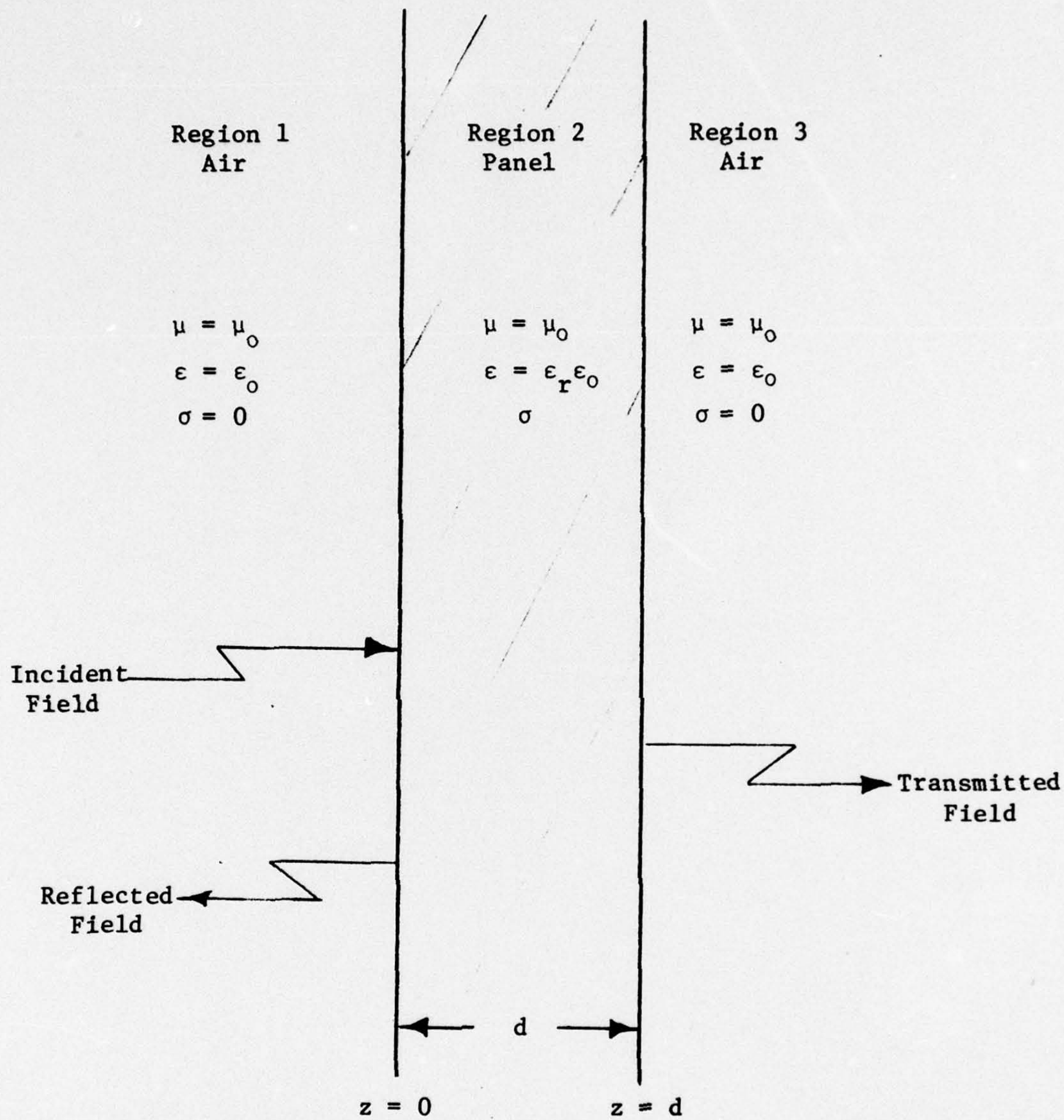


Figure 1. Model used in plane wave analysis of shielding effectiveness of panels.

The quantities E_0, E_1, E_2^+, E_2^-, and E_3 are complex constants representing the complex amplitudes of the waves. It is assumed that the incident field E_0 is known and that the transmitted field E_3 is to be found. The quantity k_i $(i = 1,2,3)$ represents the propagation constant or wave number of the wave in region i. The frequency f of the wave is related to the angular frequency ω by $\omega = 2\pi f$.

The magnetic field intensity H in each region can be determined from Maxwell's equations and will be functions of E_0, E_1, E_2^+, E_2^- and E_3. Matching the tangential E and H fields at the two boundaries of the sheet produces 4 equations in the 4 unknowns E_1, E_2^+, E_2^- and E_3 (recall that E_0 is assumed known). Solving these equations, one can obtain the power transmission coefficient

$$T = \frac{(\sin^2\delta_{12} + \sinh^2 s_{12})e^{\beta_1 d}}{\sin^2(\alpha_2 d + \delta_{12}) + \sinh^2(\beta_2 d + s_{12})} \tag{1}$$

where

$$T = \left|\frac{E_3}{E_0}\right|^2$$

$$\alpha_i = \omega\left[\frac{\mu_i\varepsilon_i}{2}\left(\sqrt{1 + \frac{\sigma_i^2}{\varepsilon_i^2\omega^2}} + 1\right)\right]^{1/2} \qquad i = 1,2$$

$$\beta_i = \omega\left[\frac{\mu_i\varepsilon_i}{2}\left(\sqrt{1 + \frac{\sigma_i^2}{\varepsilon_i^2\omega^2}} - 1\right)\right]^{1/2} \qquad i = 1,2$$

$$s_{12} = -\frac{1}{2}\ln R_{12}$$

$$R_{12} = \frac{(\mu_2\alpha_1 - \mu_1\alpha_2)^2 + (\mu_2\beta_1 - \mu_1\beta_2)^2}{(\mu_2\alpha_1 + \mu_1\alpha_2)^2 + (\mu_2\beta_1 + \mu_1\beta_2)^2}$$

$$\tan\delta_{12} = \frac{2\mu_1\mu_2(\alpha_2\beta_1 - \alpha_1\beta_2)}{\mu_2^2(\alpha_1^2 + \beta_1^2) - \mu_1^2(\alpha_2^2 + \beta_2^2)}$$

The quantity T represents the shielding effectiveness of the panel since it equals the ratio of the power transmitted through the panel to the power incident on the panel. Equation 1 was evaluated numerically and compared with data in the literature, and the agreement has been very good. These and other checks indicate that the formula is accurate.

Figures 2 and 3 present the results of some of the data obtained using Equation 1. Figure 2 shows the shielding effectiveness of various 9 mm thick panels versus frequency. A panel thickness of 9 mm was selected since it is nearly equal to 0.36 inches which is the thickness of the panels supplied by AMMRC. The curves in Figure 2 are for conductivities between 1 and 10,000 Siemens/meter. Increasing the conductivity of the panel increases its shielding effectiveness as expected. For each value of conductivity, the shielding effectiveness of the panel was calculated for three values of dielectric constant for the panel, namely 1, 4, and 16. In all cases the permeability of the panel was assumed to be equal to that of free space which is usually true for non-magnetic materials. Varying the dielectric constant between 1, 4 and 16, produced such small changes in shielding effectiveness that they were imperceptible when plotted on a graph. Thus the curves in Figure 2 apply for any value of dielectric constant for the panel up to 16. The dielectric constant of typical matrix material used in the panels is about 4 in an unfoamed state. Presumably it is less in a foamed state. Thus, Figure 2 applies to the panels of interest. The lack of dependence of the curves on dielectric constant is important since it says that the matrix material used in the panel has very little effect on shielding effectiveness as long as the conductivity of the panel is greater than 1 Siemen/meter. Thus the conductive properties of the array of fibers in the panel determines the shielding properties and not the matrix material. Figure 2 shows that a conductivity of about 300 S/m or greater must be achieved in the panel to obtain 50 dB or more of shielding effectiveness. Shielding effectiveness of at least 50 dB is typically required for military equipment.

Figure 3 is a plot of shielding effectiveness versus panel thickness with frequency and panel conductivity as parameters. Again as with Figure 2, the curves in Figure 3 do not change when the dielectric constant of the panel is varied from 1 to 16. Typical panel thickness of interest varies between 1/4 and 3/8 inches (roughly 6 to 10 mm) according to AMMRC. Figure 3 shows that a conductivity of about 400 will be required for 6 mm thick panels at 10 MHz to obtain 50 dB of shielding effectiveness. For a σ = 100 S/m panel, increasing the panel thickness from 6 to 10 mm increases the shielding effectiveness by 4 dB at 10 MHz, by 7 dB at 100 MHz and by 22 dB at 1000 MHz. Figure 3 shows that increasing conductivity rather than increasing panel thickness is more effective for obtaining 50 dB of shielding

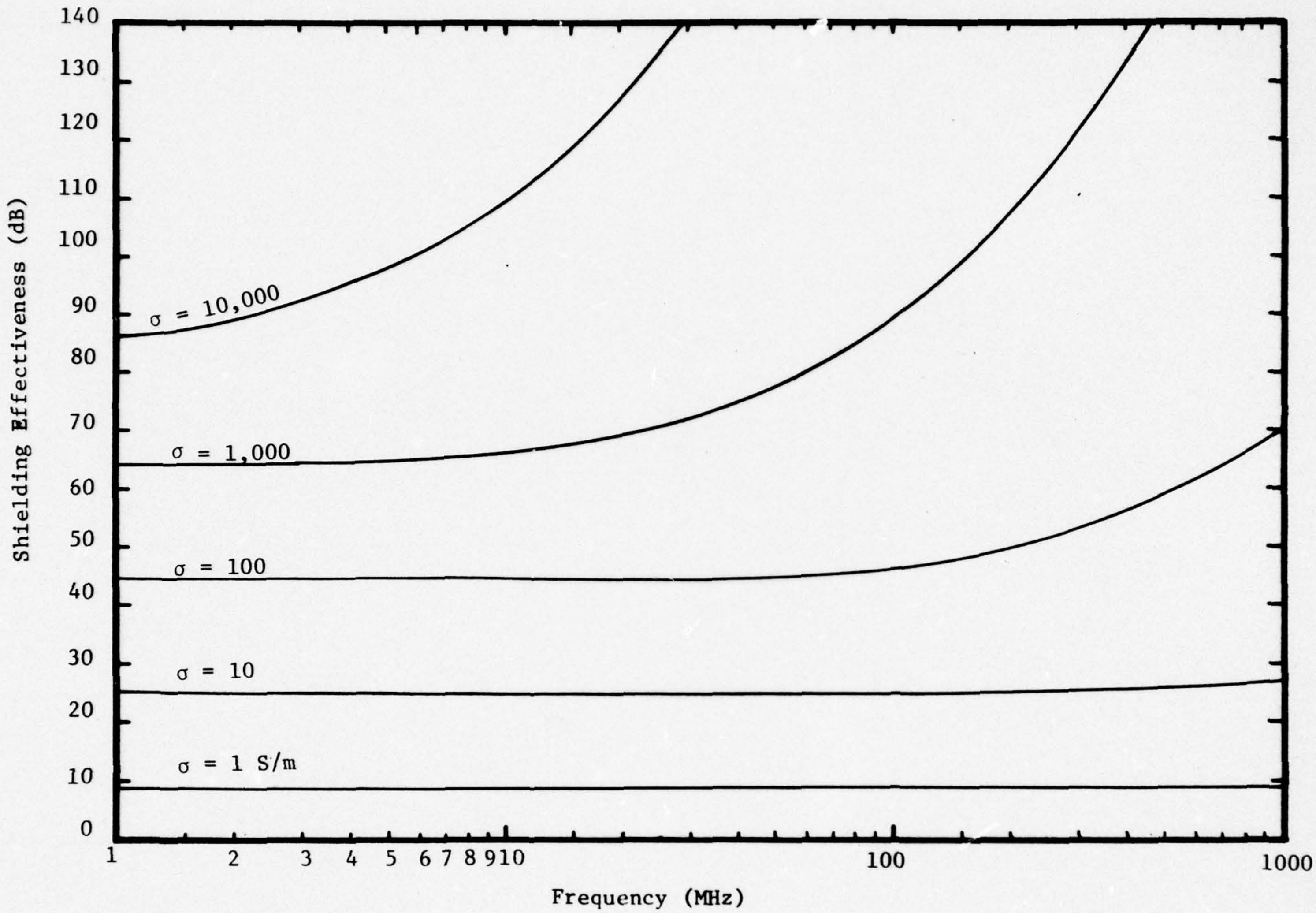


Figure 2. Plane wave shielding effectiveness of 9 mm thick planar panels versus frequency.

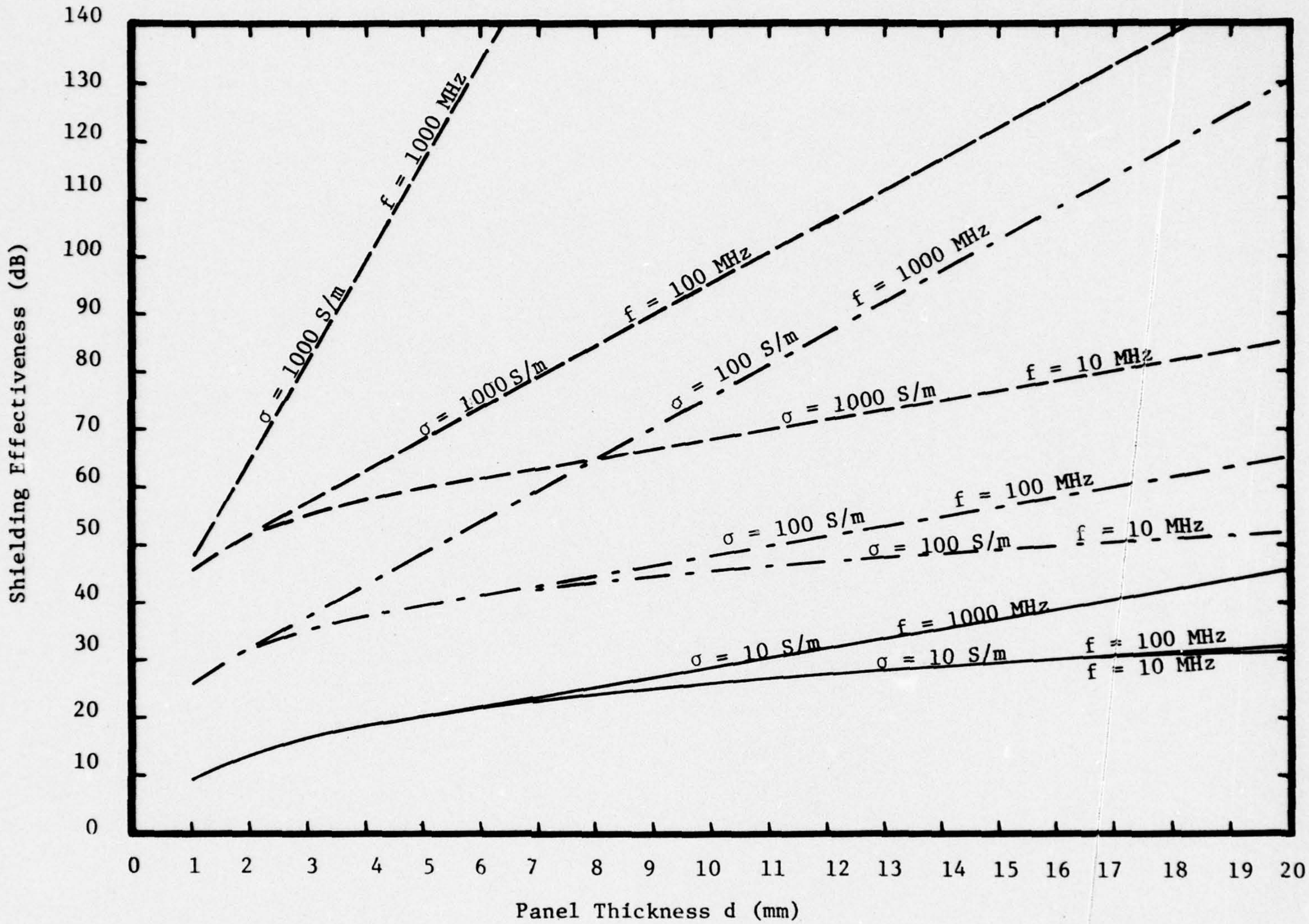


Figure 3. Plane wave shielding effectiveness of planar panels versus panel thickness.

effectiveness at HF and VHF frequencies for the range of panel thicknesses that are of interest.

The principal difficulty with the plane wave analysis comes in assigning an effective conductivity to the network of particles in the foam. As discussed in Section IIE, an exact calculation of the conductivity of the panel appears impossible. Attempts are still being made at an approximate analysis. Section IIIB presents some measurements of the conductivity of several panels supplied by AMMRC. As discussed in that section, the predicted shielding effectiveness based on the measured conductivity and on Figure 2 agrees well with measured values of shielding effectiveness given in Section IIIA. The conductivity measurements of Section IIIB showed a maximum value of about 30 S/m for the current AMMRC panels. Figure 2 shows that the conductivity of the panel must be increased by about one order of magnitude in order to obtain 50 dB or more of shielding. Materials that should produce such conductivity are discussed in Sections IIE and IIF.

B. Moment Method Analysis

A very powerful technique for analyzing electromagnetic problems is the moment method [1] first formulated by Harrington. It can in principle analyze a wide variety of conductor geometries, including arbitrarily oriented conductors and lossy conductors. Because of its ability to handle a wide range of parameters, the moment method was given careful consideration for the shielding effectiveness analysis of this program. Some of the features of moment method analysis will be discussed first followed by applications for the problem at hand.

The moment method formulates the problem of interest in terms of an operator equation of the form

$$L(f) = g \tag{2}$$

where L is a known operator, g is a known function and f is the unknown function that is to be determined. The unknown function f is expanded in terms of a known set of basis functions $\{\phi_n\}$ with unknown coefficients $\{C_n\}$ such that

$$f = \sum_n C_n \phi_n . \tag{3}$$

A set of known testing functions $\{w_m\}$ is then used to test (2) after (3) is substituted into (2). This operation yields

$$\sum_n C_n < w_m, L(\phi_n) > \; = \; < w_m, g > \tag{4}$$

where <> stands for the inner product and the linearity of the operator L has been used in obtaining (4). The advantage of the formulation used in (4) is that the operator equation for the unknown function f has been replaced by a matrix equation for the unknown constants $\{C_n\}$. Let N functions be used in (3) to represent f. If (4) is performed for each of N different testing functions $\{w_m\}$, then (4) represents N equations in N unknowns. Standard matrix techniques can be used to solve this system of equations for the unknowns $\{C_n\}$.

A great deal of work has been done on applying moment method techniques to wire antennas [2]. Carbon fibers are short, lossy wires and so can be analyzed by these wire antenna, moment method techniques. The operator equation corresponding to (1) for a single wire is a Fredholm integral equation of the first kind and is given by [2]

$$E_z^i(z) = \int_{-L/2}^{L/2} K(z,z')I(z')dz' \tag{5}$$

$E_z^i(z)$ is the component of the known incident electric field tangent to the wire, $K(z,z')$ is the known kernal of the equation, and $I(z')$ is the unknown current at point z' on the wire. The incident field can be specified for the electromagnetic problem of interest and can be a plane wave, an electric near field, or a magnetic near field. Knowing E and K in (5), one can solve for I by representing it as a sum of known functions with unknown coefficients as in (3) and then forming the inner product as in (4).

A large number of wires instead of a single wire is of interest for the loaded structural foam problem. The moment method can also be used to analyze a conducting body consisting of multiple wires. The current in each wire is expanded in a known functional form with an unknown amplitude. These unknown amplitudes are determined using matrix techniques via the moment method. The number of wires that can be analyzed by such a technique is conceptually unlimited. In practice, however, the number of wires (actually the total number of expansion functions) that can be treated is limited to 300 to 500 due to computer storage, round-off, and speed limitations.

The carbon fibers in the foam form a dense chaff-like cloud which tends to scatter incident energy back to the source and let little energy through the cloud. A report by Garbacz [3] discusses the application of moment method techniques to chaff clouds. A cloud of resonant (half wavelength) dipoles illuminated by a plane wave source is analyzed. Galerkin's method is used in which the testing and basis functions are identical. Each dipole is conceptually split into two segments and the current on each segment is represented by a piecewise sinusoidal current of unknown amplitude and phase. The coupling (i.e., mutual impedance) between each segment of current and any other segment (or itself) can be expressed in the form of a reaction integral (i.e., an inner product integral) based on the reaction matching technique of Richmond [4]. The significant fact which makes the reaction matching technique attractive is that all the reaction integrals may be evaluated in closed form, thereby permitting the rapid determination of all elements in the impedance matrix. Garbacz says that the largest chaff cloud that they can handle consists of 250 chaff elements due to computer storage limitations. This limitation is consistent with results obtained by Georgia Tech and others. Typical spacings between dipoles was $\lambda/2$ or greater (λ = free space wavelength) for the Garbacz work. He states that his results become unreliable when the average inter-element spacing is $\lambda/8$ or smaller. More than two current segments per dipole are then required to accurately represent the current in the presence of strong mutual coupling between the chaff elements. Increasing the number of current segments per wire decreases the number of chaff elements that can be analyzed. For example, a 200 dipole cloud can be solved with two-segment models while only a 22 dipole cloud can be solved using a four-segment model, according to Garbacz.

According to AMMRC, the carbon fibers typically used in the foam panels to date have been 1/8 to 1/16 inch long. Since λ = 11,800 inches at 1 MHz and λ = 11.8 inches at 1 GHz, typical fiber lengths of interest vary from $\lambda/(1.9 \times 10^5)$ to $\lambda/94$. Since these fiber lengths are orders of magnitude smaller than those used by Garbacz, it might be possible that a one-segment current model might be usable even though the fibers are very close together. Thus, the moment method could be used as long as total number of fibers in a panel was small enough. A formulation different from Garbacz's would, of course, have to be used.

Measurements made on typical panels loaded with carbon/graphite fibers gave a relatively low DC resistance indicating that a substantial number of fibers are in electrical contact. This situation is desirable for providing good shielding. However, it complicates the analysis since it suggests that a large number of fibers is present in a panel. Some simple calculations were performed to determine if the number of fiber segments in a typical panel was consistent with that which the method of moments can handle. Typical panels made by AMMRC are 30 to 40% fibers by weight and have a 30% density reduction due to air in the panel. The density of the plastic in the panel is ρ_p = 1.1 to 1.2 g/cm^3 while that of the fibers is ρ_f = 2.1 g/cm^3. The fibers are typically 1/16 inch long and 10 μm in diameter. A typical AMMRC panel is 7.94 inches on a side, 0.36 inches thick and weighed 300 grams. An estimate of the number of fibers in the panel was made based on these values. The total weight W_f of the fibers in the panel is 120 grams assuming that the panel is 40% fibers by weight. The number N_f of fibers in the panel is given in terms of the diameter D_f and the length L_f of the individual fibers as

$$N_f = \frac{4W_f}{\pi D_f^2 L_f \rho_f} .$$

Using the above values, $N_f = 4.6 \times 10^8$ or 1.2×10^6 fibers per cubic centimeter are present in the panel. The method of moments, however, cannot handle this number of fibers. It could handle a cube a few hundredths of a centimeter on a side but this volume is too small compared to the wavelength of operation to provide useful information.

Several workers in the area of moment method techniques were contacted to see if the technique could be used to analyze a large number of contacting wires. The impression obtained from these discussions is that although some improvements could be made over conventional moment method approaches, the improvements would not be substantial enough to solve the problem at hand.

Due to the above consideration, alternate analysis techniques were pursued. One approach that was examined is to treat the panel as a lossy dielectric material (see Section IIA). This model seems reasonable due to the relatively large number of contacting fibers present in the panel.

Plane wave reflection and transmission coefficients can be obtained to investigate the shielding properties of the panel based on this model. A cruder model which will be presented next is obtained by using a periodic wire grid to model the array of fibers.

C. Wire Grid Model

It is instructive to examine several electromagnetic scattering geometries in order to determine some of the dominant characteristics of conductively impregnated structural foam. The first question that will be examined is how closely the internal fibers must be in order to provide effective shielding. This problem will be addressed first by approximating the fibers as an array of infinitely long, identical, parallel, perfectly conducting wires as shown in Figure 4. Although this is a very crude model it is useful in illustrating an important point. Let the wires have a diameter, D, and a spacing, S, and let a plane wave having a wavelength, λ, be incident normal to the grid. The incident electric field may be polarized either parallel (i.e., $E_{\parallel}$) or perpendicular (i.e., $E_{\perp}$) to the axis of the wires. The equivalent circuit of the grid as seen by the incident wave is given by Marcavitz [5] and is shown in Figure 5. When $S/\lambda \ll 1$ the circuit parameters are:

$$\frac{X_a}{Z_o} = \frac{S}{\lambda}\left[\ln\left(\frac{S}{\pi D}\right) + 0.601\left(\frac{S}{\lambda}\right)^2\right] \tag{6}$$

$$\frac{X_b}{Z_o} = \frac{S}{\lambda}\left(\frac{\pi D}{S}\right)^2 \tag{7}$$

$$\frac{B_a}{Y_o} = \frac{S}{2\lambda}\left(\frac{\pi D}{S}\right)^2 \frac{1}{A_2} \tag{8}$$

$$\frac{B_b}{Y_o} = \frac{2\lambda}{S}\left(\frac{S}{\pi D}\right)^2 A_1 - \left(\frac{S}{4\lambda}\right)\left(\frac{\pi D}{S}\right)^2 \frac{1}{A_2} \tag{9}$$

where

$$A_1 = 1 + \frac{1}{2}\left(\frac{\pi D}{\lambda}\right)^2 \left(\ln\frac{S}{\pi D} + \frac{3}{4}\right)$$

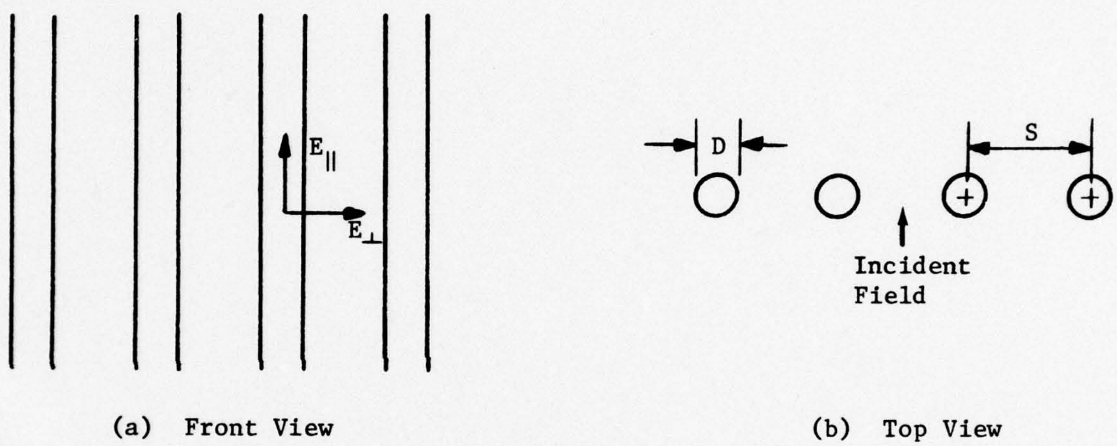
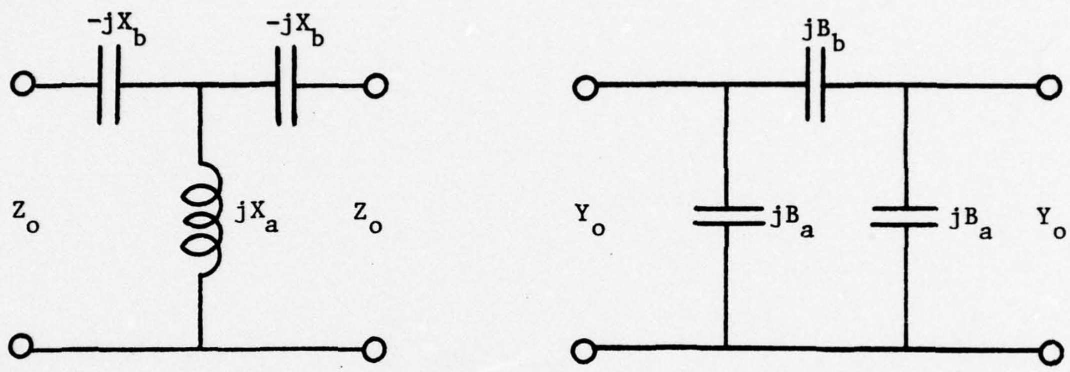


Figure 4. Wire grid approximation of structural foam filled with fibers.



(a) For Parallel Polarization

(b) For Perpendicular Polarization

Figure 5. Equivalent circuit of wire grid at normal incidence.

$$A_2 = 1 + \frac{1}{2} \left(\frac{\pi D}{\lambda}\right)^2 \left[\frac{11}{4} - \ln \frac{S}{\pi D}\right] + \frac{1}{24\pi} \left(\frac{\pi D}{S}\right)^2$$

and Z_o and Y_o are the characteristic impedance and admittance of free space, respectively.

An inspection of (6) and (7) reveals that X_a and X_b approach zero as λ becomes large. Thus, the inductor in Figure 5a shorts the transmission line at low frequencies and little power is transferred to the opposite side of the grid. Thus, the grid acts as an effective shield to parallel polarization at low frequencies. An inspection of (8) and (9) reveals that B_a approaches zero and that B_b becomes large as λ gets large. Thus, the shunt capacitors in Figure 5b act as open circuits and the series capacitor acts as a short as λ gets large. This situation indicates that a large amount of energy travels past the grid and that the grid is not an effective shield for perpendicular polarization.

The amount of power passing through the grid is plotted in Figure 6. The power transmission coefficient, T, is plotted in this figure and is the ratio of the power passing through the grid to the power incident on the grid in decibels. Figure 6 indicates, for example, a transmission loss of 40 dB for parallel polarization and only 0.001 dB for perpendicular polarization when $S/\lambda = 0.038$ and $D/S = 0.28$.

The question now arises as to whether the good shielding characteristics for parallel polarization are the result of the wires simply being longer in the axial direction or is it the fact that the wires are infinitely long in that direction. What would the shielding characteristics be if one replaces the infinitely long wires of Figure 4 with a two dimensional array of short wires? It turns out that the shielding characteristics are bad for both polarizations as will be shown next. The conclusion to be drawn from all of this is that a large number of noncontacting fibers does not provide effective shielding. Only by having long conductive paths can good shielding be obtained.

A model for the fibers consisting of short, noncontacting plates is shown in Figure 7. This is a more realistic model than that of Figure 4. The model in Figure 7 consists of a doubly-periodic array of thin rectangular plates. Analysis of such structures has been performed by Chen [6] and by Montgomery [7]. Chen analyzes an infinite array of thin plates arranged in a doubly-periodic grid and analyzes the fields in terms of a set of Floquet mode functions. For an arbitrarily polarized plane wave incident from an

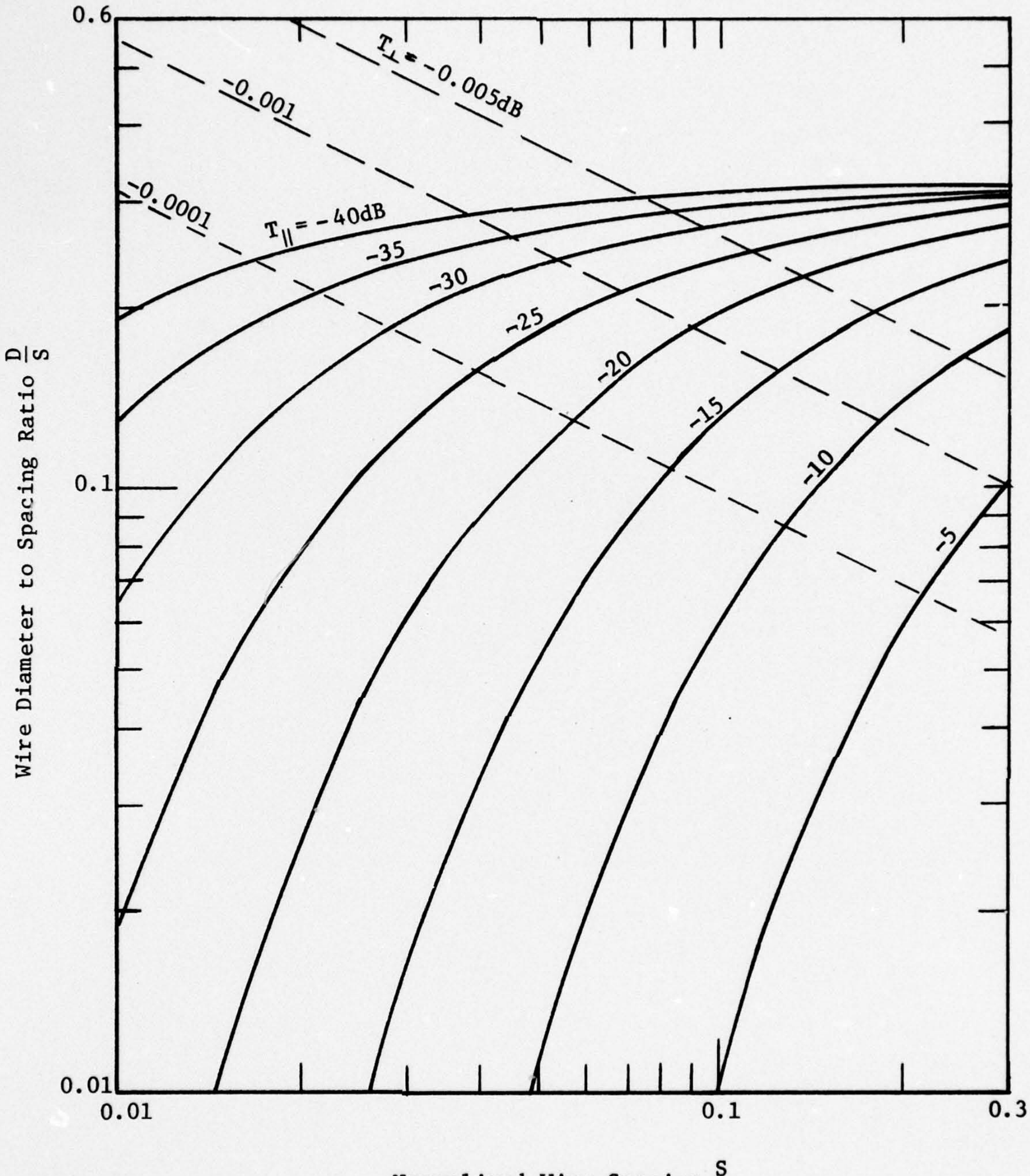
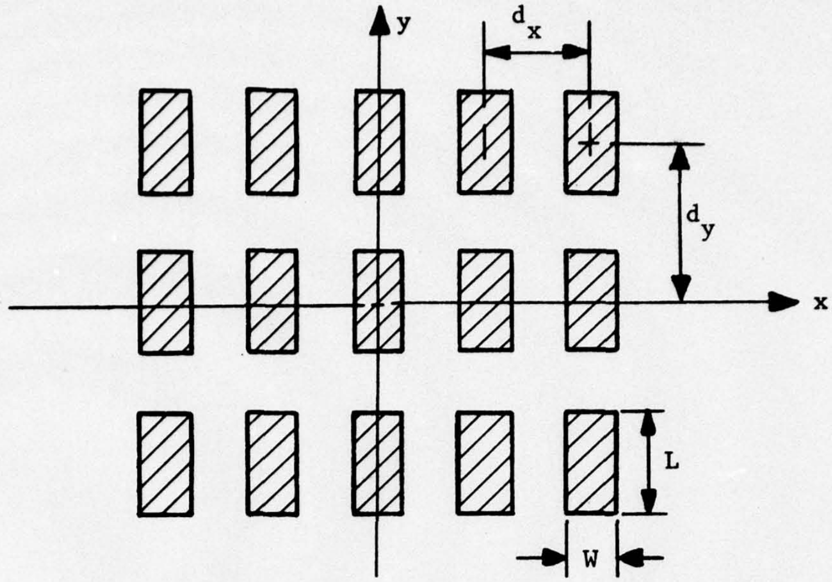
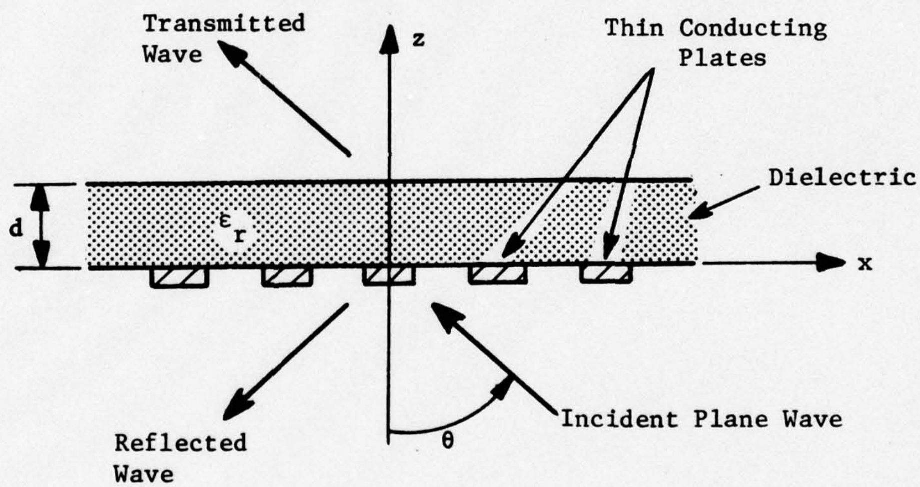


Figure 6. Transmission coefficient for parallel polarization and for perpendicular polarization for a grid of round wires.



(a) Front View



(b) Top View

Figure 7. Model consisting of an infinite periodic array of thin conducting plates on a dielectric sheet.

oblique angle, he obtains the current on the plate using moment method techniques. From this current he calculates the near-field distribution, the distant reflected wave as well as the reflection coefficient from the structure. Montgomery treats the same problem of a doubly-periodic array of thin conductors, but on a dielectric sheet. He also uses Floquet modes for representing the field and obtains via moment methods a system of equations for solving for the same type of field quantities that Chen considered.

Both Chen and Montgomery provide general equations for analyzing their respective problems. These equations must be programmed for a digital computer to obtain numerical results. Sample calculations are presented by both authors, but no general design information is presented. However, there is a trend in Chen's data that is useful. Chen presents data for strips that are from 1.27 to 1.35 cm long, are 0.127 to 0.508 cm wide, and are spaced from 0.76 to 2.54 cm apart. His data shows that 100% of the incident power is reflected (i.e., maximum shielding) near 10 to 11 GHz and that the amount of reflected power decreases rapidly with frequency. Only from 5 to 30% of the power is reflected at 8 GHz. Thus, these arrays provide less than 1.6 dB of shielding at 8 GHz. Chen presents data only as low as 6 GHz, but his data shows the amount of reflected power monotonically decreasing as the frequency of the incident wave decreases.

One should expect the amount of scattered power to decrease with decreasing frequency. For objects that are small compared to the wavelength λ of the incident field, Lord Rayleigh's law states that the reflected power from the object is proportional to λ^{-4}. Thus, if a foam panel has a fixed number of small conducting objects in it that are not contacting, the amount of shielding provided by the panel decreases rapidly with decreasing frequency according to Lord Rayleigh's law. This conclusion is consistent with Chen's calculations discussed above.

The preceding analysis has shown that noncontacting fibers that are electrically small (i.e., are much smaller than a wavelength in their major dimension) do not provide effective RF shielding. This conclusion is true even when the number of fibers is large. The wire grid model discussed above reveals that long conductive paths in the direction of the incident electric field are required for effective shielding. Thus, a large number of contacting fibers is required in the foam material to provide effective shielding. Conductive paths must be present in at least two orthogonal directions normal to the incident field to provide shielding for an arbitrarily polarized

incident field. Unfortunately, the wire grid model cannot be used to analyze finite length conductors that are not periodic. Hence it is not a general purpose analysis tool for structural foam that is internally loaded with conducting material.

D. Meteorological Model

A great deal of theoretical and experimental work has been performed in the field of meteorological radar. The fundamental calculation of the scattering and absorption of electromagnetic waves by a dielectric sphere is due to Mie and is given in Stratton [8]. Extensive calculations of attenuation, based on Mie's results, have been carried out for rain, hail, fogs and clouds and this data is reported in Kerr [9]. These and other calculations are based on either noncontacting, noninteracting particles or on noncontacting and interacting particles. As was shown in Section IIC, a substantial number of contacts is required between particles to achieve effective shielding from the loaded structural foam. Such a geometry does not appear to be treated in the meteorological radar literature. Hence, meteorological models were abandoned for this study.

E. Predicting Electrical Properties of Panels

The electrical characterization of composite materials is receiving increased attention due to recent use of such materials in aircraft and missiles. Use of these materials is also being contemplated in antennas in order to achieve high dimensional stability as is required for high performance antennas. For the purposes of RF shielding, the effective conductivity (or inversely, the resistivity) of the composite must be known. The higher the effective conductivity the more the composite behaves electrically like a conductor and hence the more shielding that it can provide. The use of carbon fibers in structural foam represents a difficult electromagnetic analysis problem. First of all, the fibers are to some degree wet by the matrix material (which is usually an insulator) and so have an insulating shell around them. Secondly, there is a contact resistance between fibers when they come in physical contact due to their surface properties. Finally the orientation and density of the fibers in the structure is a complicated function of the manufacturing process.

The carbon fibers to be used in RF enclosures made from structural foam are normally received embedded in a matrix material and cut in the form of

pellets. The matrix material adheres to the fibers to provide good structural properties. Since the matrix material is usually an insulator, each fiber appears roughly like a wire with an insulating sheath around it. This sheath inhibits electrical conduction between fibers. In addition to this inhibiting factor, surface properties of the fibers and low pressure between fibers tend to retard inter-fiber conduction. The carbon fibers will typically have water, oil and some atmospheric gases absorbed into their surfaces. These surface impurities along with the matrix material constitute an insulating film around the fiber.

Electrical conduction between fibers through the insulating layer can occur in several ways [10, 11]. Because of the wave nature of electrons and because of the distribution of their energies, a certain portion of the electrons can pass through (designated the tunneling effect) a thin film of insulating material, or rather, through a potential barrier which, in the classical sense, would be impenetrable. If the film is less than 20 Angstroms thick, conduction through the film can occur by this tunneling effect. The film acts as an ohmic resistance as long as the voltage across the film does not exceed about 0.5 volts. Films that are 100 Angstroms or more in average thickness are called thick films. Conduction by the tunneling effect can be neglected at these thicknesses. Aside from mechanical fracturing of the film to allow intimate fiber-to-fiber contact, the only other way that current can flow efficiently is to electrically puncture the thick film. Such electrical puncture is called fritting. When the voltage level across a thick insulating film reaches about 10^5 to 10^6 volts/cm, electrons start to flow in selected areas of the film. The areas of current flow are those where the film is thinnest or where its composition makes it more conductive than elsewhere.

This complicated process of forming conduction paths through the network of fibers in a panel makes an exact analysis impossible. Several approaches to obtain an approximate analysis have been attempted. The most promising approach thus far utilizes concepts from the kinetic theory of gases. Work is still being performed in this area. One relationship that has come out of this analysis is that long, thin fibers are better than short, fat ones in regard to improving shielding effectiveness. The reason for this can be explained as follows. Consider a volume of foam with fibers in it. Consider

the situation of either long, thin fibers or short, fat ones with the volume of each fiber being fixed. For a fixed number of fibers in the foam, the concentration by weight will be the same for the long and for the short fibers. However, since the fibers are randomly oriented, there is a much greater probability of fiber contact for the long fibers since they can rotate through a much larger volume. In addition, long fibers scatter energy better than short ones as was seen in Section IIC. Thus the conductivity of a panel made from long, thin fibers should be higher than one made from short, fat fibers for the same concentration of fibers by weight.

Several concepts can be obtained from the analysis of Section IIC as to the general nature of the electrical properties of conductively loaded panels. When the conducting particles (be they grains or fibers) are widely separated, there is no contact between particles and hence no significant shielding. Appreciable conductivity starts when the number of particles per unit volume becomes large enough so that there is a significant probability of contact between particles. For 100% concentration, the conductivity of the panel will be that of the particles. Thus, the conductivity of the panel versus particle concentration curve will start at essentially zero for zero concentration, stay at zero until the concentration is high enough to cause significant physical contact between particles, and then rise and finally approach the conductivity of the particles for 100% concentration. The concentration at which the conductivity begins to increase from zero depends on the particle characteristics. As will be seen in Section IIIB, a 30% concentration of aluminum coated glass fibers has a much lower conductivity than a 10% concentration of carbon/graphite fibers. This difference is probably due to an oxide layer on the aluminum which inhibits interfiber contacts and low fiber conductivity due to the thinness of the coating.

Carbon and graphite fibers can be made from precursors of rayon, polyacrylonitrile (PAN), or pitch. The principal application of rayon was, until recently, in the manufacture of cord for automobile tires. However, rayon is no longer used in tires and the sources of rayon fiber have almost completely ceased production. Fibers made from pitch are typically more highly graphitized and have a higher modulus than PAN fibers. Pitch fibers also show longer ordering of crystals in the fiber than do PAN fibers. Since there is a direct relationship between the fiber's modulus and its basal plane conductivity, the higher the modulus the higher will be the

conductivity of the fiber. This appears to be caused by a stronger alignment of the crystal basal planes with the fiber axis as the modulus increases.

The above considerations suggest the use of pitch based fibers with as high a modulus as possible to achieve the highest electrical conductivity possible and hence the best shielding. It appears that the present panels made by AMMRC use PAN-based Hercules AS fibers. The fiber conductivity could be increased by about a factor of 10 by using a high modulus pitch fiber such as Union Carbide VM0034, TP4104B, or TP4101. An alternate material that should be considered if the preceding ones cannot be obtained is the PAN-based fiber GY-70 made by Celanese. Its conductivity is about 3 times better than Hercules AS and so should produce a factor of 3 increase in conductivity instead of the factor of 10 that is required for 50 dB of shielding effectiveness (see Section IIA). The fibers just recommended have good surface contact properties in addition to having high bulk conductivity and are recommended for use in Phase II of the program.

F. Alternate Materials

Materials other than carbon/graphite fibers were considered for internally loading the structural foam. Metalized glass fibers, metal powders and magnetic (high permeability) powders were considered. Metalized glass fibers are often used as chaff material and so are readily available. The conductivity of metal coated fibers can be much higher than that of carbon/graphite fibers depending on the thickness of the metal and so have the potential of providing better shielding. The conductivity will be low, however, if a thin, discontinuous metal coating is used. Aluminum is the metal typically used to coat the glass fibers. Aluminum suffers from an oxide layer that quickly builds up on its surface and which inhibits conduction between fibers (a property of little concern in chaff work). Section IIIB presents measured conductivity data showing substantially worse performance from metalized glass fibers than from carbon/graphite fibers. Gold coated fibers would not build up an oxide surface layer like aluminum and would have a much higher conductivity than the carbon/graphite fibers. However, it does not appear that gold fibers would be economical. Thus metalized glass fibers do not offer a practical method for improving shielding effectiveness.

Metallic powder, in particular silver powder, is used commercially in conducting pastes and calking materials for RFI shielding applications. Conversations with one of the manufacturers of such material, namely Emerson &

Cuming, revealed that the concentration of silver powder had to be about 80% (the exact value is company proprietary) in order to achieve satisfactory shielding. Such a concentration would not be economical and would not produce the desired mechanical properties from the foam panels. Lower concentrations will produce less shielding as is the case with the use of fibers in the foam. The amount of shielding achievable from lower concentrations such as 30% is not known. A review of measured data [12] taken at Georgia Tech on higher concentrations suggests that large particles provide better shielding than do fine ones. This is expected to be the case for lower concentrations also. This same report also indicates that high permeability powders such as carbonyl iron or ferrite powders such as General Ceramics, Inc. T-1,0-3 or H provide higher absorption loss than do metal powders. The metal powders on the other hand provide higher reflection loss but little absorption loss. Thus a combination of metallic and magnetic powders in one panel is recommended in an attempt to achieve both high reflection and high absorption loss. Alternate materials which might be less expensive but have the same electrical properties are made by the Metals Division of the Glidden Company. Glidden material number D-290 is similar to carbonyl iron and M-180 to General Ceramics H type ferrite powder. The ferrite powders are recommended [12] over carbonyl iron since they have higher loss at low frequencies than does carbonyl iron. Silver is recommended for the metal powder.

III. PRELIMINARY MEASUREMENTS

A. Shielding Effectiveness Measurements

Preliminary shielding effectiveness measurements were performed on panels supplied to Georgia Tech by AMMRC. Measurements were performed utilizing two dipole antennas and a metal box with a rectangular aperture (hole) in it. The measurement configuration used is shown in Figure 8. The measurement process proceeded as follows. After setting the signal generator frequency, both antennas are adjusted to resonant length. The signal level at the receive antenna is recorded with the panel removed. The panel is then placed over the aperture and the received signal level recorded. The difference of these two signal levels is the shielding effectiveness.

Figure 9 shows a comparison between calculated and measured shielding effectiveness performed using the above technique on hardware cloth made of 0.040 inch diameter galvanized steel wires spaced on a 0.5 by 0.5 inch grid. This figure indicates that the experimental setup performs well down to about 250 MHz. At lower frequencies the box appears to be too small electrically to provide adequate data. Other tests indicate the data should be accurate up to about 650 MHz. No attempt was made to improve the measurement geometry since that would be done during Phase II of the program. Only quick look measurements were of interest during this phase of the contract.

Figure 10 shows data taken on a 1/8 inch thick aluminum plate using the same measurement setup. This measurement was made to see how tightly the box, and the connecting cables, had been sealed to RF energy. The maximum measured shielding effectiveness was 53 dB while the typical value was 35 to 45 dB. The theoretical value is 2,400 dB or greater from 50 to 800 MHz. Thus enough energy is leaking through the measurement equipment to limit the maximum measurable value of shielding effectiveness to about 35 to 45 dB.

The preceding tests indicate that certain improvements to the equipment will be required during Phase II of the contract. Greater care will have to be exercised in making the measurement enclosure in order to measure larger values of shielding effectiveness. Basically this involves using better RF seals where cables enter the box. Further effort is required in the selection of antennas to permit operation at frequencies below 250 MHz. Loop antennas should permit measurements to much lower frequencies.

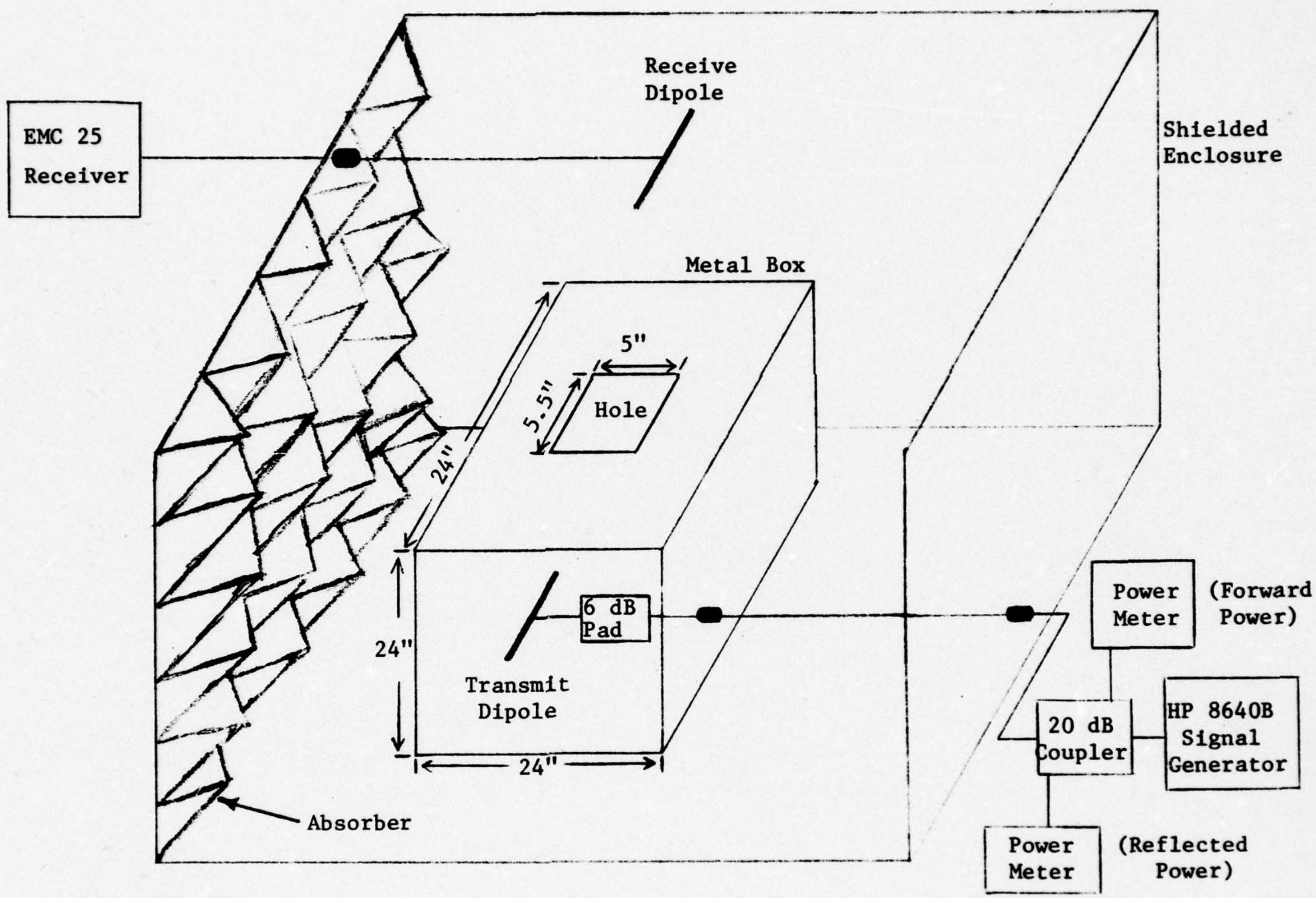


Figure 8. Equipment configuration used in measuring shielding effectiveness.

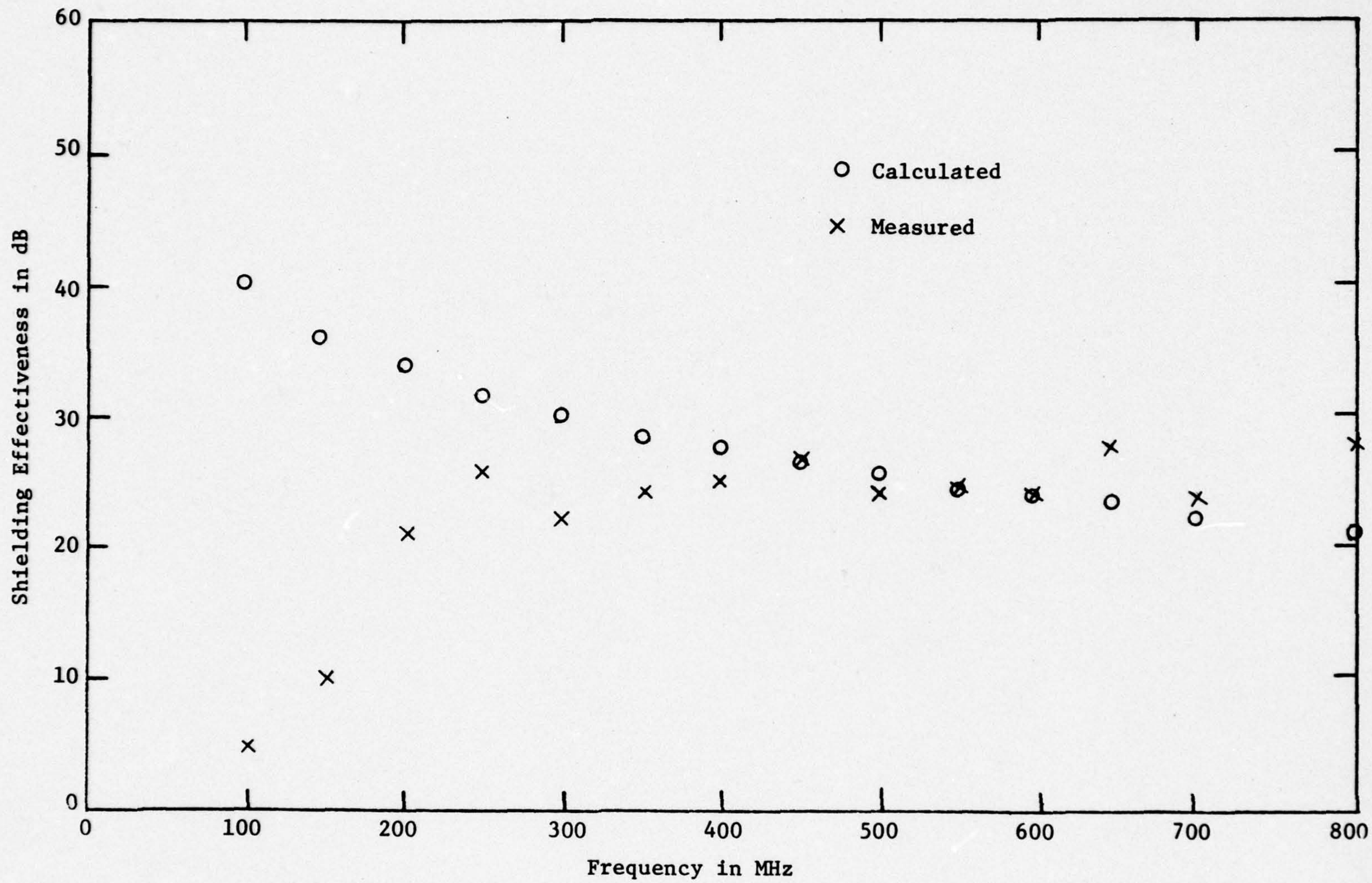


Figure 9. Comparison of measured and calculated shielding effectiveness of 0.5 by 0.5 inch hardware cloth.

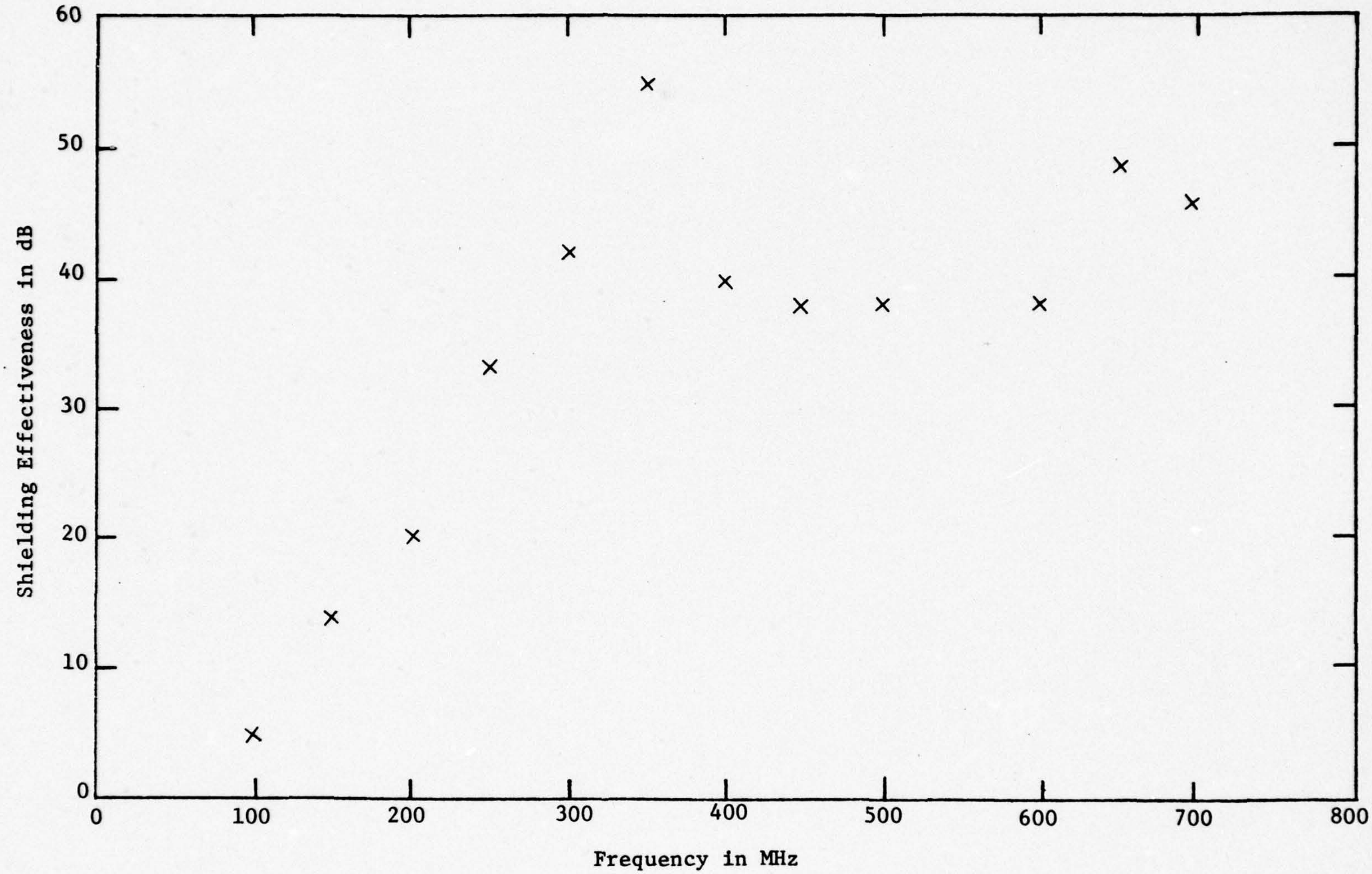


Figure 10. Measured shielding effectiveness of 1/8 inch thick, flat aluminum plate.

Having established the range of validity of the measurement equipment from the previous measurement, data was taken on the previously mentioned panels. One set of panels was reinforced with carbon fibers while the other set was reinforced with aluminum coated glass fibers. Two panels each were received containing 10, 20 and 30% by weight of carbon/graphite reinforced thermoplastic polyester. All of the aluminum coated glass reinforced polycarbonate panels had 30% fibers by weight. Two of these glass panels were foamed, two were unfoamed and made with a reciprocating screw, and two were unfoamed and made with a plunger machine. The shielding effectiveness of these panels was measured in the same manner as above. Figures 11 and 12 present the results of these measurements. Figure 11 shows a dramatic improvement in shielding effectiveness when the fiber concentration is increased from 10% to 20%. The improvement is not nearly so great when the concentration is increased from 20% to 30%.

Over the frequency range where the data should be valid, the shielding effectiveness for the 30% graphite fiber panel increased from about 20 dB at 250 MHz to about 40 dB at 650 MHz. This amount of shielding is typical of that obtained from consumer oriented electronic equipment. However, good quality military and commercial electronic equipment usually provide 50 to 80 dB of shielding effectiveness. Thus, the test sample falls short of providing effective shielding for military gear especially at the VHF frequencies (30 - 300 MHz). At UHF frequencies (300 - 1000 MHz) the panel might be sufficiently effective but the present measurement process is not accurate enough to determine this. Better measurements will have to be made during Phase II of the program.

Figure 12 shows that little shielding effectiveness is obtained from the aluminum coated glass fibers. The poorer performance of the aluminum coated fibers may be due to oxidation of the aluminum which would produce poor electrical contact between fibers thus reducing shielding effectiveness. Negative values of shielding effectiveness are erroneous results produced by diffraction.

B. Conductivity Measurements

The DC resistance of each of the sample panels was measured by placing each panel in succession between two parallel aluminum plates and measuring the resistance between these plates (see Figure 13). The conductivity of the aluminum plates is much higher (3.54×10^7 Siemen/meter) than that of the panels and so the finite conductivity of the plates should introduce

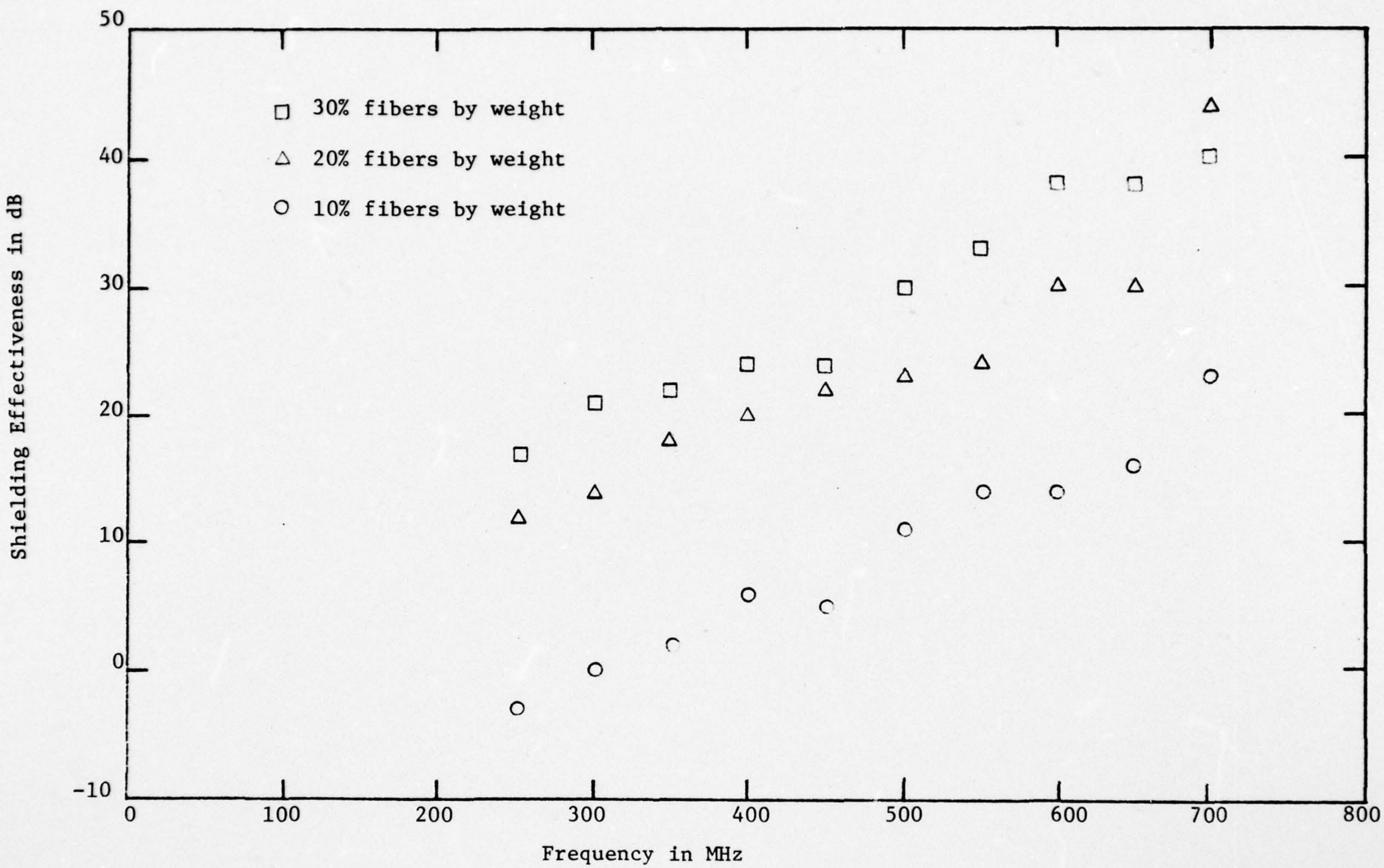


Figure 11. Measured shielding effectiveness of carbon/graphite reinforced thermoplastic polyester panels 0.36 inches thick.

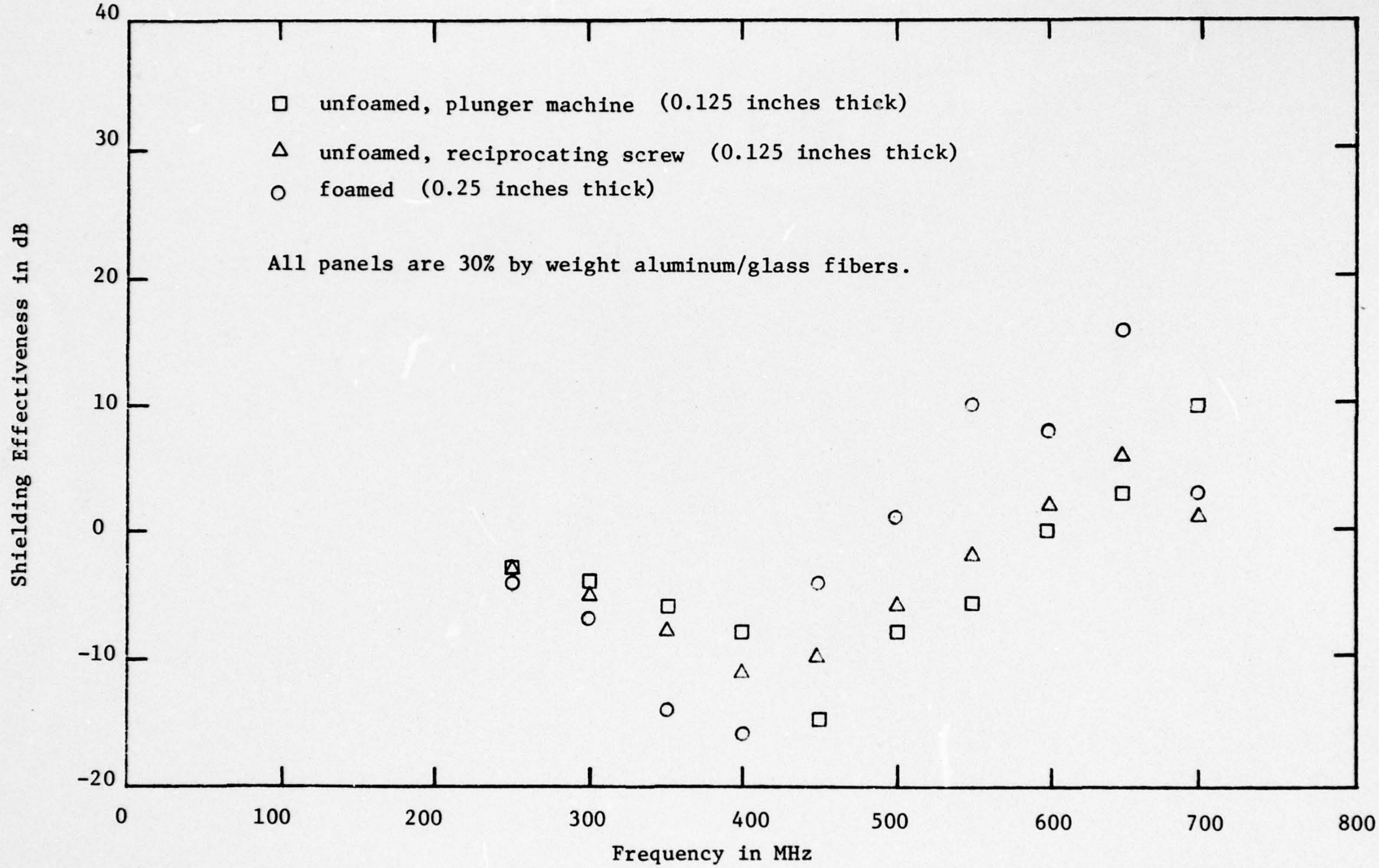


Figure 12. Measured shielding effectiveness of aluminum coated glass reinforced polycarbonate panels.

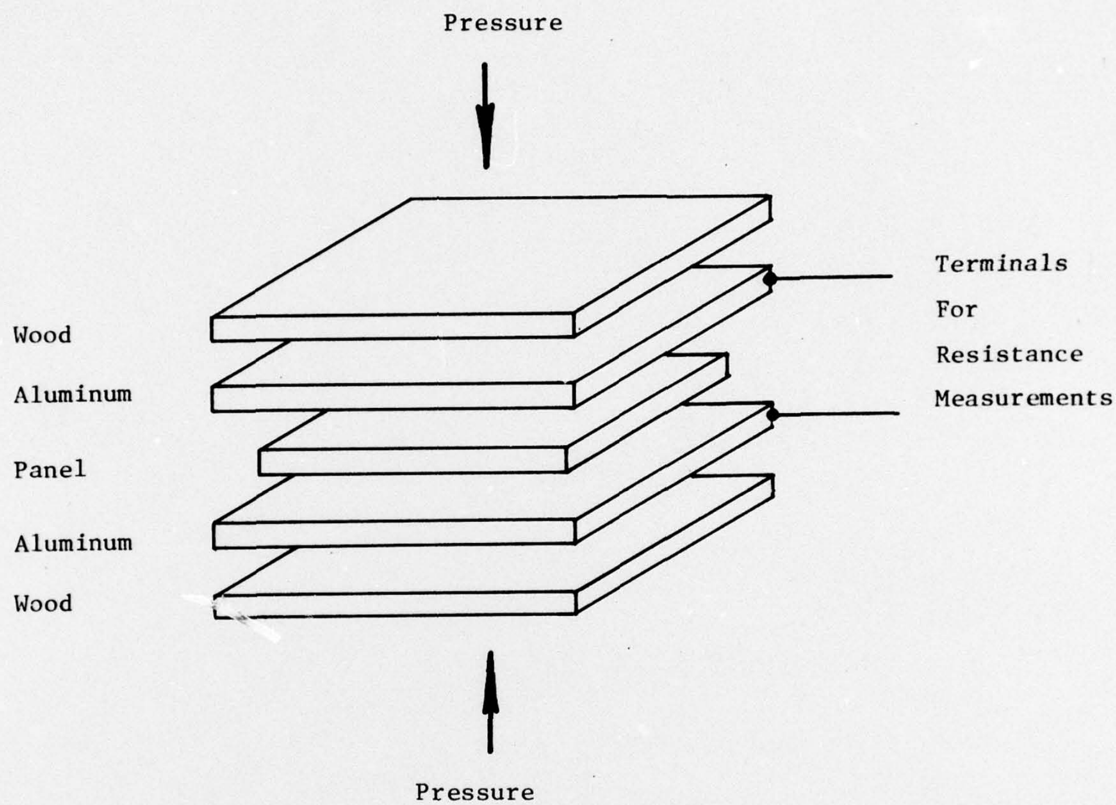


Figure 13. Configuration used in measuring resistance of panels.

negligible error in the measurements. It is important in determining conductivity that the plates make good contact at all points on the surface of the panel. This turned out to be difficult to accomplish since the panels are not flat. After trying several techniques a repeatable measurement technique was found. The panel was first sandwiched between two aluminum plates. Then a flat piece of wood was placed over the outside of each of the plates. Several C-clamps were next used to squeeze the two pieces of wood together thus forcing the aluminum plates into contact with the panels. The clamps were tightened while making resistance measurements until the lowest resistance reading was obtained. This condition indicated that maximum contact with the panel was being made. Finally the conductivity of the panel was calculated from the formula

$$\sigma = \frac{H}{LWR}$$

where

σ = conductivity of the panel

H = height of panel between the parallel plates

L = length of panel

W = width of panel

R = resistance of panel measured between the parallel plate.

Two resistance measurements were made on each panel, one between the broad faces of the panel and the other between two opposite edges. These measurements were performed to determine whether the injection of fibers into the panel mold produced preferential fiber orientation and hence anisotropic conductivity. Table I presents the results of the conductivity calculations based on these resistance measurements. It can first of all be seen from this table that the carbon fibers produce a much more conductive panel than do the aluminum coated glass fibers. This is significant since all of the aluminum coated glass fiber panels had 30% fibers by weight and yet they performed worse than a carbon fiber panel with only 10% fibers by weight. The poorer performance of the aluminum coated fibers is probably due to oxidation of the aluminum which would produce poor electrical contact between fibers. Carbon fibers, however, do not have this problem.

Table I also shows that there is a preferential orientation of the fibers in the panels made of carbon fibers. Presumably the same effect would be seen in the aluminum coated fiber panels if their resistance could

TABLE I

COMPUTED CONDUCTIVITY OF FIBER REINFORCED PANELS BASED ON RESISTANCE MEASUREMENTS

A. Carbon Fiber Reinforced Thermoplastic Polyester[1] Structural Foam Panels*

% Fiber by Volume	% Fiber by Weight	Conductivity (Siemens per meter) Broadside	Edge	Size
7.4	10	6.1×10^{-3}	8.4×10^{-2}	8" x 8" x 3/8"
15.3	20	2.0×10^{-1}	1.3×10^{1}	8" x 8" x 3/8"
23.6	30	7.0×10^{-1}	3.1×10^{1}	8" x 8" x 3/8"

B. Aluminum Coated Glass Fiber Reinforced Polycarbonate[2] Panels[3]

Construction	% Fiber by Volume	% Fiber by Weight	Conductivity (Siemens per meter) Broadside	Edge	Size
Foamed*	16.8	30	3.5×10^{-4}	**	8" x 8" x 1/4"
Unfoamed, Reciprocating Screw	16.8	30	**	**	8" x 8" x 1/8"
Unfoamed, Plunger Machine	16.8	30	**	**	8" x 8" x 1/8"

---

* Panels foamed to 80% of theoretical solid density.

** Means too small to measure, i.e., less than 10^{-9} S/m.

1 LNP Carbon Fiber Reinforced Thermoplastic Polyester (WC-1006).

2 MBAssociates, San Ramon, California - Aluminum coated glass fiber - .9 mil diameter glass fiber, .05-.1 mil aluminum coating (99.9% pure).

3 Compounded by Fiberfil, Evansville, Indiana into 3/8" long polycarbonate (Mobay - M60 grade) pellets.

be measured. One would expect the majority of the fibers to orient parallel to the panel walls during the injection molding process. Thus better electrical conduction would be expected parallel to the panel walls than perpendicular to it. This is indeed the case as can be seen from Table I.

The edge conductivity is the value that should be used in evaluating shielding effectiveness based on the plane wave analysis of Section IIA. This is because currents flowing parallel to the broad faces of the panel are responsible for causing shielding by the panel. From Table I it can be seen that σ varies from 0.08 to 31 for the three carbon fiber panels tested. In the 250 to 650 MHz range, Figure 2 shows that the theoretical value of shielding effectiveness should vary between 5 dB and 40 dB for this range of conductivity. The measured values of shielding effectiveness given in Figure 11 agree quite well with these theoretical values.

IV. SUMMARY AND RECOMMENDATIONS

The analysis performed under the first phase of the program and which is summarized in this report was oriented toward obtaining trends in shielding effectiveness (SE) versus material parameters of structural foam internally loaded with conductive materials (SFILCM). Several analysis techniques were considered including moment method, wire grid, meteorological, and plane wave analysis.

The salient aspects of the findings assembled in this report can be summarized as follows.

1. A large number of contacting particles or fibers is required in the foam to provide significant SE.
2. The moment method is not applicable for analyzing SFILCM since it cannot handle the very large number of particles involved. However, using a periodic wire patch model for the conducting particles, the moment method provides insight into the low frequency SE of the SFILCM.
3. The wire grid model is inadequate for SFILCM analysis since it assumes that all fibers are contacting their nearest neighbors. It does, however, lend insight into the need for contacting particles to obtain SE.
4. Meteorological models are not applicable to SFILCM since they utilize non-contacting particles.
5. Plane wave analysis provides an adequate analysis tool for SE evaluation of SFILCM. The principal difficulty with this technique is associating an effective conductivity to the network of contacting fibers. Analysis is still being performed in this area.
6. The dielectric constant of the structural foam does not affect the SE of SFILCM as long as its value is less than 16 and as long as the conductivity of the SFILCM is greater than 1 Siemen/meter.
7. Long thin fibers provide better SE than short fat ones.
8. To replace metal housings for radio sets in military equipment, 50 to 80 dB of SE is required from the SFILCM.
9. The conductivity of the SFILCM must be 300 to 400 Siemen/meter or greater to provide 50 dB or more of SE from 1/4 to 3/8 inch thick panels in the HF to UHF frequency range.

10. The current AMMRC panels use Hercules AS carbon/graphite fibers. These panels can provide only 20 to 40 dB of SE in the 250 to 650 MHz frequency range and so are unacceptable for replacing metal housings from an SE point of view.

11. The electrical conductivity of the current AMMRC panels must be increased by a factor of 10 to achieve the desired shielding given in 8 above. This appears feasible using the materials listed in 1 below.

As a result of the investigations on this program, the following recommendations are offered for Phase II of the program.

1. Replace the Hercules AS fibers with either Union Carbide VM0034, TP4104B, or TP4101 fibers.
2. One set of panels should be made with 3/16 inch long and another set with 1/16 inch long fibers from 1 above. Fibers concentrations of 0%, 10%, 20% and 30% by weight should be used.
3. A set of panels should be made using General Ceramics, Inc. ferrite powder T-1, 0-3 or H combined with silver powder. A 0%, 10%, 20% and 30% set of panels should be made.

If higher concentrations of fibers can be adequately processed into structural foam, as high a concentration as possible should be used instead of the 30% listed above.

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Interim Report, February 14, 1977 to August 14, 1977

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